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Beyond source restrictions: Combined mitigation strategies substantially reduce emissions and exposure of intentionally added microplastics in the United Kingdom

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Abstract

Microplastics are of environmental and public health concern due to their ubiquitous presence across ecosystems, persistence, and potential for toxicity. Among the various sources of microplastic pollution, those intentionally added to products represent a priority target for mitigation, as they can be regulated at source to reduce environmental releases. This study quantifies emissions of intentionally added microplastics in the United Kingdom from the onset of their use in key product categories through to 2043, combining historic estimates with future projections (2024–2043). Risk management options (RMOs) are evaluated for their emission reduction potential and cost-effectiveness. The analysis covers changes in product usage over time, the contribution of each sector to overall emissions, and the implications for environmental exposure. Results indicate that agricultural soils are the dominant receiving environment, mainly due to wastewater treatment delaying sludge application, followed by urban soils, driven largely by losses from synthetic sports surfaces, the largest overall emission source. Exposure modeling shows substantial buildup in soils and sediments over time, with freshwater sediments and urban soils reaching the highest predicted concentrations. Broad use-based restrictions provide the greatest exposure reductions, while targeted measures deliver compartment-specific benefits, alongside potential co-benefits such as the reduction of exposure from other contaminants. These findings provide an integrated evidence base to support targeted, sector-specific interventions and guide UK policy development to reduce microplastic pollution and protect ecosystem and human health.

Keywords: microplastics, intentionally added microplastics, emissions, environmental fate and exposure, UK pollution assessment

Introduction

Microplastics, which are plastic particles less than 5 mm in diameter, have emerged as a pervasive and persistent pollutant of growing environmental and public health concern (Alva & Thomas, 2025). Microplastic particles originate from two main categories of sources: primary microplastics, which are intentionally manufactured at small sizes and added directly to products such as cosmetics, detergents, paints, and industrial abrasives, and secondary microplastics, which are generated through the fragmentation and degradation of larger plastic items, including packaging, fishing gear, synthetic textiles, tire wear particles, and plastic litter in the environment (Rochman et al., 2019). While management options for secondary microplastics are more difficult to define, representing such a diverse range of sources and processes which may be challenging to control, intentionally added microplastics represent a more controllable pathway, as their use can be directly regulated to prevent environmental releases (ECHA, 2020).

Regulatory action on intentionally added microplastics has so far developed in two stages. Early policy measures focused on specific product groups, most notably plastic microbeads in rinse-off cosmetics and personal care products. In the United Kingdom, the manufacture and sale of such products was banned in 2018, and postimplementation evidence indicates that microbead-containing products have been successfully removed from the UK market, though direct evidence of consequent reductions in environmental microplastic concentrations

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remains limited (Defra, 2024). More recently, regulatory approaches have expanded toward broader restrictions covering multiple sectors and applications. In the European Union, Regulation (EU) 2023/2055 introduced a REACH restriction on synthetic polymer microparticles intentionally added to products, building on earlier assessments by ECHA that identified widespread emissions from these uses (ECHA, 2019; European Commission, 2023). Estimates suggest that tens of thousands of tons of intentionally added microplastics are released annually in the EU, highlighting the scale of the issue and the need for comprehensive regulatory approaches (European Commission, 2023).

However, evidence on how such regulatory measures translate into reductions in environmental exposure remains limited. While product-specific bans provide clear evidence of source removal, broader restrictions involve multiple sectors, emission pathways, transition periods, and environmental compartments, making their overall effectiveness more difficult to assess. This creates a need for integrated modeling approaches that link product use, emissions, environmental fate, and exposure over time. The present study addresses this gap by evaluating UK-relevant risk management options within a consistent modeling framework.

Intentionally added microplastics serve diverse functions across industries, from providing abrasiveness in cleaning products to improving the performance of sports surfaces (ECHA, 2020). However, once released into the environment, these particles persist for decades to centuries, contributing to long-term contamination of terrestrial, freshwater, and marine ecosystems as part of the total burden of microplastics (Jolaosho et al., 2025). Microplastics present in the ecosystem can be ingested by a wide range of organisms, including plankton and invertebrates, as well as fish, birds, and mammals (Santos et al., 2021), potentially leading to physical harm, reduced feeding efficiency, altered reproductive outcomes, and trophic transfer within food webs. Additionally, microplastics may act as vectors for additive chemicals and invasive microorganisms, further disrupting ecological processes and threatening biodiversity (Li et al., 2023).

Given concerns about their potential health and ecosystem impacts, there is an urgent need for robust estimates of emissions of intentionally added microplastics and for the evaluation of policy interventions aimed at their reduction. This paper presents the findings of a UK-focused assessment that (1) estimates both historical releases from their initial product use and future emissions until 2043, (2) identifies the primary contributing sectors, and (3) evaluates the costs and benefits of six risk management options (RMOs) designed to reduce emissions and exposure.

The results offer critical insights for policymakers aiming to address microplastic pollution at source, while also contributing to the growing international discourse on microplastics sources, emissions, and their management. Furthermore, this study identifies key data gaps and uncertainties, highlighting priorities for future research to enhance the evidence base for effective policy development.

Materials and methods

This study employed a comprehensive framework to estimate the emissions, environmental pathways, and exposure of intentionally added microplastics in the United Kingdom from their historical introduction in various sectors to 2043 (i.e., a 50-year timeframe). The period from 2024 to 2043 was selected to align with the UK policy appraisal timeframe for RMOs on intentionally added microplastics, with 2024 representing the baseline "current" year used for regulatory and economic assessment. A wide range of broad product use categories was included in the assessment to capture the diversity of applications of intentionally added microplastics in the UK market (Table 1). The dominant polymer types within each broad use category were identified based on typical functional uses in representative product types. These polymers reflect the materials most commonly employed to deliver specific performance characteristics in each application and were used to characterize sector-specific microplastic composition in the emission and exposure assessment (ECHA, 2019). The assessment was built upon the methodology developed for the EU REACH restriction proposal on intentionally added microplastics (ECHA, 2020), incorporating additional analytical steps and country-specific adjustments that fit the UK scenario. The methodology consisted of three main components: (1) emission volume data collection, (2) emission pathways analysis, and (3) exposure calculation.

Emission volume data collection

This framework integrates an understanding of emissions as a result of a comprehensive historical and projected timeline of intentionally added microplastics emissions in the United Kingdom, spanning from the inception of their use in various product categories to 2043. The analysis provides a quantitative chronicle of the introduction, proliferation, and regulatory-driven decline of these materials across key sectors in the United Kingdom. The scope is confined to intentionally added microplastics as defined within the product categories specified, which include agriculture, cosmetics, detergents, medical applications, and industrial uses (Table 1). The timeline is constructed using a dual-method approach, combining historical estimation with future projections to create a continuous dataset for each product subcategory.

Historical emission prediction

For the period preceding 2024, for which no standardized emission data exist, annual emissions were estimated through a multistep process. First, start years for each product category were identified based on published literature, patent records, and documented first commercial applications, as described in detail in the online supplementary material.

Historic emission volumes were reconstructed for each product subcategory to generate continuous annual time series from the year of first use to 2043. As consistent national statistics are largely unavailable prior to 2024, historic emissions were estimated using product-specific logistic adoption curves representing gradual market uptake. This approach assumes that product use follows a technology diffusion pattern, where adoption increases from low initial penetration to near-saturation over time. Logistic functions were parameterized using two constraints: (i) a low initial adoption level at the start year, and (ii) a product-specific time-to-saturation reflecting differences in

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Table 1 Broad use categories, example product types, and typical polymers used for intentionally added microplastics.

Broad use category	Example product types	Primary polymers used
Agriculture and horticulture	Controlled release fertilizers (CRF), fertilizer additives, treated seeds, plant protection products, soil conditioners, seed coatings	PUR (polyurethane), PVAc (polyvinyl acetate), PMMA (polymethyl methacrylate)
Cosmetic products	Rinse-off cosmetics, leave-on products (moisturizers, deodorants), lipsticks, powders, liquid emulsions, super-absorbents, carriers for other ingredients	PAA (polyacrylic acid)
Detergents and maintenance products	Waxes, polishes, air care products, abrasives, fragrance encapsulations, surface cleaners, fabric softeners, dishwashing liquids, and microbead-containing detergents	PAA
Medicinal products	Ion exchange resins, controlled release medicines, active pharmaceutical ingredients (APIs), immediate release formulations, diffusion-controlled systems, osmotic systems	PAA, PMMA
In vitro diagnostic devices	Reagents, assays, calibration products, chromatography columns, and ultrasound devices	PS (polystyrene)
Materials used in synthetic sports surfaces	Infill material for synthetic sports fields, materials used in equestrian arenas	SBR (styrene-butadiene rubber)
Oil & gas	Additives in drilling and production chemicals (lubricants, friction reducers, antifoam agents, demulsifiers)	PVC (polyvinyl chloride)[a]
Paints, inks, and coatings	Consumer and professional uses, polymer dispersion binders, architectural and industrial coatings, printing inks, laser printing toners	PMMA, PAA, PTFE (polytetrafluoroethylene)

[a] No information on the types of polymers could be found, and a worst-case assumption of PVC was assumed to be representative of a conservative assumption for microplastics in this sector.

market diffusion rates across product types. These parameters were used to reconstruct annual emission trajectories that are consistent with the observed 2024 baseline values. Full mathematical formulation and parameterization are provided in the online supplementary material.

To our knowledge, such a systematic reconstruction of historic microplastic emissions has not previously been undertaken in a chemicals policy context. It should be noted that this reconstruction relies on a combination of limited empirical data, literature-derived estimates, and modeling assumptions. In particular, the use of logistic adoption curves introduces uncertainty related to the timing and rate of market uptake, which cannot be fully validated due to the absence of consistent historical datasets.

For most product categories, the 2024 emission level was assumed to be close to market saturation, defined here as a stage where product use has reached a stable or slowly varying level following widespread adoption and market maturity. This assumption was based on observed market data trends, regulatory timelines, and sector-specific knowledge of product use patterns, including evidence from UK market statistics and projections used in the Defra option appraisal for intentionally added microplastics (Defra, 2025). Historic emissions from the year of introduction to 2023 were therefore back-calculated using a logistic function describing gradual market uptake and scaled to pass exactly through the observed 2024 emission volume. Product-specific time-to-saturation ranges, informed by product type and qualitative uptake speed, were used to parameterize the logistic growth.

For four product categories, such as care products (in vitro diagnostics); medicinal products; sports surfaces; and paints, inks, and coatings, emissions were projected to continue increasing for several years beyond 2024 in the baseline scenario due to delayed regulatory phase-out timelines under the EU REACH restriction. For these categories, market maturity had not yet been reached by 2024. Accordingly, the logistic carrying capacity was approximated from the projected plateau in the 2024–2043 emission scenario, and growth parameters were calibrated using projected emission levels for 2024 and 2027. This ensured consistency between historic reconstruction and anticipated post-2024 transition dynamics.

In all cases, reconstructed values were applied only to the historic period (from product introduction to 2023). Emission volumes for 2024–2043 were retained exactly as specified in the

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baseline scenario. A full description of the data sources, start-year selection, and mathematical parameterization of the logistic models is provided in the online supplementary material.

Future emission projection

To estimate the projection of intentionally added microplastics entering the UK market, a market-based approach was used. For each relevant product category, the total volume of microplastics added annually (tons/year) was estimated based on market size, product use patterns, and the prevalence of microplastic-containing formulations.

Data sources for emission estimates were drawn from multiple complementary inputs. The primary dataset was the PRODCOM database from the UK Manufacturers' Sales by Product (Defra, 2025; Office for National Statistics (ONS), 2024), which provides detailed information on turnover and production volumes across various industrial product categories relevant to microplastic use. In addition, UK-specific stakeholder data were collected through targeted interviews with industry associations (Defra, 2025). Key sectors such as fertilizers, oil and gas, and synthetic sports surfaces provided comprehensive and sector-specific volume estimates. For product categories where no UK-specific data were available, estimates were adapted from the ECHA background report (ECHA, 2020) with values scaled to the UK context using market share and population-based scaling factors to ensure national relevance. This combination of data sources and scaling approaches is consistent with those applied in the Defra option appraisal for intentionally added microplastics, which similarly integrates national statistics, stakeholder input, and EU-derived datasets to inform UK-specific assessments (Defra, 2025). As with many material flow analyses (MFAs) (Bornhöft et al., 2016; Brunner & Rechberger, 2016), the emission estimates are subject to uncertainty arising from data gaps, reliance on proxy data, and the need for scaling assumptions. Where direct measurements were unavailable, values were derived from the literature or expert judgment and should therefore be interpreted as indicative rather than definitive.

Future market trends were projected using historical turnover data combined with expert judgment on sectoral growth patterns. The analysis accounted for anticipated regulatory impacts from the EU REACH restriction for traded product categories, assuming that approximately 80% of UK manufacturers supplying EU-linked markets would align their formulations with EU standards according to the relevant transition timelines (European Commission, 2023). This assumption was applied only to product groups subject to international trade and regulatory convergence. Locally applied uses, such as sports surfaces and oil and gas applications, were assumed to remain largely unaffected by EU regulatory alignment, and their future emissions were projected based primarily on domestic market trends. Data inputs for emission estimation were derived from a combination of UK national statistics (e.g., PRODCOM/ONS), stakeholder data, regulatory reports (e.g., ECHA), and literature sources. Where direct UK data were unavailable, values were adapted from EU-level assessments and scaled to UK conditions using population and market-based factors.

Risk management options

Six RMOs were evaluated to assess their effectiveness in reducing emissions and exposure to intentionally added microplastics, each compared against a baseline "business-as-usual" scenario. The RMOs include regulatory restrictions on use as well as downstream and use-specific emission control measures. A summary of the scope and key features of each option is provided in Table 2. A detailed description of the development, underlying assumptions, and evaluation of these RMOs is provided in the Defra options appraisal report (Defra, 2025).

The effectiveness of each RMO was assessed by comparing modeled emissions and predicted environmental concentrations (PECs) under each scenario against the baseline (business-as-usual) case. For each RMO, changes in total emissions, pathway-specific emissions, and compartment-specific exposure were quantified over time (2024–2043). This allowed evaluation of both overall emission reduction efficiency and the distribution of benefits across environmental compartments. In addition, comparisons across RMOs were used to assess relative effectiveness in targeting specific pathways and reducing long-term accumulation in key receiving environments (Defra, 2025).

Three RMOs focus on restricting the use of intentionally added microplastics. Risk management option 1A (RMO 1A) proposes a broad restriction across nearly all applications, with limited derogations for essential uses such as medical devices and in vitro diagnostic devices. This RMO is expected to achieve near-complete elimination of emissions by the end of the considered timeframe. Risk management option 1B (RMO 1B) represents a more targeted restriction, focusing on the largest emitting sectors: cosmetics, detergents and maintenance products, oil and gas, and materials used in synthetic sports surfaces. This targeted approach reflects the RMO screening process, which balances effectiveness, financial impacts, and practicability. By prioritizing the main emission sources, RMO 1B aims to achieve substantial emission reductions while maintaining greater feasibility for industry implementation. Longer transition periods and derogations are included for lower-emitting uses where substitution is more technically challenging, associated with higher uncertainty, or expected to impose disproportionate economic or administrative burdens (Defra, 2025). Risk management option 1C (RMO 1C) aligns UK regulation directly with the EU REACH restriction on intentionally added microplastics, adopting the same scope, derogations, and phase-out timelines.

Three RMOs address emissions through specific risk management measures. Risk management option 2 (RMO 2) targets materials used in synthetic sports surfaces by introducing mandatory risk management measures to prevent the loss of infill materials, including physical containment, dedicated maintenance practices, and behavioral controls, aiming to substantially reduce releases from this high-emitting use. Risk management option 3A (RMO 3A) and risk management option 3B (RMO 3B) address downstream emissions by reducing the recycling of sewage sludge to land by 95% and 50%, respectively, thereby limiting the transfer of microplastics retained during wastewater treatment to soils (Defra, 2025).

Together, these six RMOs represent a spectrum of policy approaches, ranging from broad regulatory restrictions at source to targeted and downstream measures, allowing comparison of

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Table 2 Summary of risk management options (RMOs) assessed.

RMO	Type of measure	Scope/targeted uses	Key risk management approach	Indicative emission reduction[a]
RMO 1A	Broad restriction	All intentionally added microplastics, except derogated essential uses (e.g., medical devices, in vitro diagnostics)	Near-complete ban on use of intentionally added microplastics, with limited derogations and short transition periods	∼100%
RMO 1B	Targeted restriction	Largest emitting uses: cosmetics, detergents and maintenance products, oil and gas, and materials used in synthetic sports surfaces	Restriction focused on high-emission sectors, with longer transition periods and derogations for lower-emitting uses	∼72%–87%
RMO 1C	Regulatory alignment	Uses within the scope of the EU REACH restriction	UK restriction aligned with EU REACH, adopting the same scope, derogations, and phase-out timelines	∼72%–100%
RMO 2	Use-specific risk management measures	Materials used in synthetic sports surfaces (infill materials)	Mandatory emission prevention measures such as pitch barriers, containment, dedicated maintenance equipment, and behavioral controls	∼28%
RMO 3A	Downstream emission control	Sewage sludge is recycled to land	Reduction of sewage sludge recycling to land by 95%, diverting sludge to alternative treatment or disposal routes	∼48%
RMO 3B	Downstream emission control	Sewage sludge is recycled to land	Reduction of sewage sludge recycling to land by 50%, with partial diversion to alternative treatment or disposal routes	∼25%

[a] Emission reduction percentages refer to reductions relative to the baseline (“do nothing”) scenario in 2043.

effectiveness, costs, and wider environmental and societal impacts. In practice, regulatory decision-making involves balancing trade-offs between environmental effectiveness, cost-effectiveness, and technical feasibility, with options typically designed to achieve substantial emission reductions while minimizing economic and practical burdens; as a result, no single option is universally optimal across all impact categories (Defra, 2025).

Emission pathway assessment

The emission pathways of intentionally added microplastics were modeled using a material flow analysis (MFA) approach, which is commonly applied in pollution modeling to track the movement of materials through human and environmental systems (ECHA, 2020; Schwarz et al., 2023). For each product category, the specific routes by which microplastics may enter the environment were systematically mapped based on how the product is used, its life cycle, and associated waste management practices. These pathways were then quantified by applying transfer coefficients to represent the proportion of microplastics following each route.

Two main categories of emission pathways were considered: direct emissions and indirect emissions via wastewater systems (Figure 1). Direct emissions occur when microplastics are released straight into the environment during product use or disposal. For example, microplastics are directly applied to agricultural land through fertilizer, emitted to the atmosphere or terrestrial surfaces through abrasion of synthetic sports surfaces, or enter surface waters via direct industrial discharges or outdoor product use (such as construction materials or coatings).

Indirect emissions occur when microplastics first enter the wastewater system before being transferred to various environmental compartments. For products such as detergents, cosmetics, and cleaning agents, a significant fraction of microplastics is washed down household or industrial drains and enters wastewater treatment plants (WWTPs). Based on recent UK studies (UKWIR, 2022a, 2022b), approximately 96% of generated wastewater is treated at WWTPs, while 4% bypasses treatment via combined sewer overflows (CSOs) and misconnections (see online supplementary material for calculation). Of the microplastics that enter WWTPs, 99% are captured in biosolids (made from sewage sludge), and the remaining approximately 1% is released with treated effluent into surface waters (UKWIR, 2022a, 2022b).

The fate of biosolids is an important secondary pathway for environmental release. While wastewater treatment processes are generally effective at removing microplastics from the aqueous phase, this removal largely reflects their transfer from wastewater into sewage sludge rather than their destruction or permanent elimination. As a result, microplastics are concentrated in the sludge generated during treatment. Current data indicate that 94% of biosolids are applied to agricultural land

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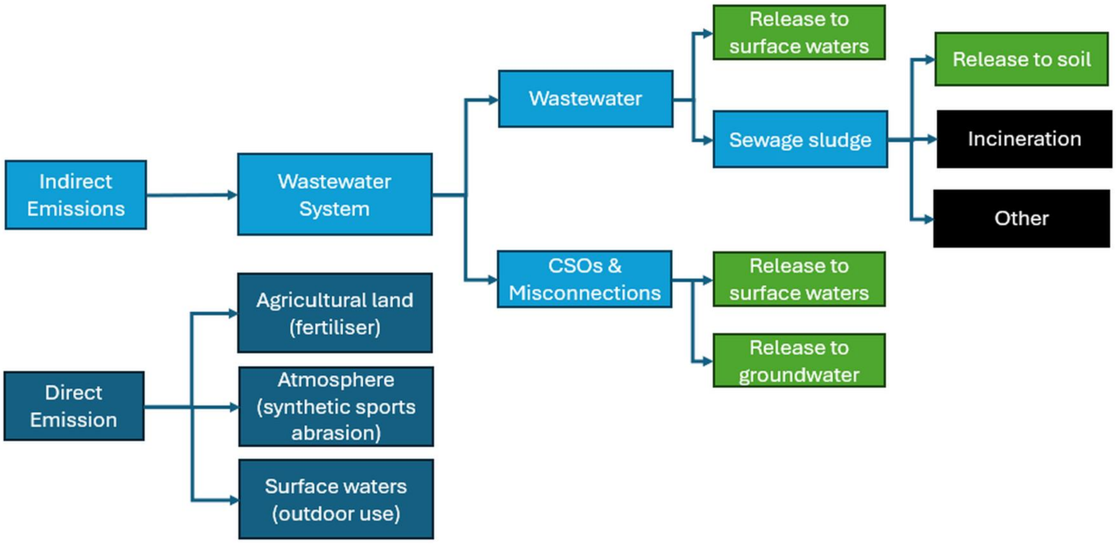

Figure 1 Conceptual framework of emission pathways for intentionally added microplastics, divided into two main categories: direct emissions and indirect emissions via wastewater systems. Direct emissions (dark blue) occur when microplastics are released directly into the environment during product use or disposal. Indirect emissions (light blue) occur when microplastics enter the wastewater system, with most treated at wastewater treatment plants and bypassing via combined sewer overflows (CSOs) and misconnections. Releases to the environment are shown in green, while those in black (incineration and other uses) are considered not to reach the environment.

(Defra, 2022), with the remainder either incinerated (3%) or used in other applications, such as land reclamation (3%). Consequently, even when wastewater treatment substantially reduces emissions to surface waters, a significant fraction of intentionally added microplastics may still enter terrestrial environments through the land application of biosolids. In addition, CSOs represent an intermittent but significant pathway for emissions to surface waters, especially during periods of heavy rainfall when sewer systems overflow directly into watercourses. Recent estimates suggest that 89% of CSO-derived microplastics are discharged to rivers, 10% to coastal or estuarine waters, and 1% to groundwater (Defra, 2021)

This quantitative mapping of emission pathways was critical for accurately modeling the ultimate environmental distribution of intentionally added microplastics. For each product category, the initial annual use estimates (see section, *Emission volume data collection*) were combined with transfer coefficients for each emission pathway, enabling calculation of the amount of microplastic (tons/year) entering key environmental compartments: surface waters, sediments, soils, and air. The material flow analysis approach provides a structured framework for linking emissions to environmental compartments; however, it is inherently dependent on transfer coefficients and pathway assumptions that may vary across regions and over time. These coefficients were derived from the best available literature and UK-specific studies but remain a key source of uncertainty in the model outputs.

Exposure assessment

The exposure assessment used the UTOPIA model, a comprehensive framework designed to simulate how microplastics spread and what their ultimate fate is in the environment. It is based on the Full Multi model introduced by Domercq et al. (2022). The UTOPIA model simulates the transport, transformation, and fate of microplastics across 17 distinct environmental compartments (such as rivers, soil, and air). Plastics are grouped into five size categories, from nanometers to millimeters, and tracked in four states: free, heteroaggregated, biofouled, and both biofouled and heteroaggregated (Domercq et al., 2025).

Originally built to determine the final, steady-state distribution of microplastic mass and particle counts, the model was enhanced for this project to also provide dynamic (time-dependent) predictions. United Kingdom-specific parameters were applied to reflect national environmental conditions, waste management practices, and emission pathways. A full description of the UK-specific parameterization of the UTOPIA model, including input datasets and assumptions, is provided in the online supplementary material.

Results

Emission

Baseline (business-as-usual) emissions of intentionally added microplastics were quantified across major use sectors and environmental compartments from the start year of commercial use for each product category through to 2043. Figure 2 presents results for two reference years, 2024 and 2043, representing the baseline "current" year used for policy appraisal and the end of the analytical period, respectively.

In 2024, agricultural soils represent the largest sink for intentionally added microplastics. This dominance is driven primarily by the application of sewage sludge (biosolids) to agricultural land, as approximately 99% of microplastics entering wastewater treatment plants are retained in biosolids rather than discharged in effluent. Consequently, sectors whose emissions occur predominantly via wastewater pathways, most notably

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detergents and cosmetics, contribute substantially to soil contamination despite moderate use volumes. Smaller fractions of these emissions are transported to freshwater via releases in WWTP effluent and, subsequently, the marine environment.

Urban soil constitutes the second-largest receiving compartment. Emissions to urban soil are driven almost entirely by materials used in synthetic sports surfaces, particularly rubber and polymeric infill. The assumption was made that direct emissions from sports surfaces to soil would be in urban areas, rather than to agricultural or other soils. Although the majority of infill materials are assumed to remain on-site, the large quantities in use lead to substantial cumulative emissions over time. These emissions arise from processes such as mechanical abrasion during use, displacement of infill particles beyond pitch boundaries (including by players and machinery displacing infill material), and transport via surface runoff during precipitation events (Defra, 2025; ECHA, 2020; Magnusson & Macsik, 2020). This pathway dominates urban soil contamination and contributes indirectly to freshwater emissions via surface runoff.

Among the use sectors, materials used in synthetic sports surfaces are the largest overall source of intentionally added microplastic releases into the environment in 2024, followed by detergents and cosmetic products. The high contribution from sports surfaces is primarily attributable to large annual use volumes, rather than high emission fractions. In contrast, detergents and cosmetics exhibit near-complete emission of their microplastic content during use, due to efficient transfer to wastewater systems and, ultimately, agricultural soils. It should be noted that this assessment is limited to intentionally added microplastics and does not include other major sources such as tire wear particles, road dust, or textile fiber emissions, which are known to contribute substantially to total environmental microplastic loads. This focus reflects the greater potential for regulatory intervention, as intentionally added microplastics arise from identifiable product uses and therefore represent emissions that can be more directly controlled compared to more diffuse secondary sources. Within the scope of intentionally added microplastics considered here, the high contribution from sports surfaces is primarily attributable to large annual use volumes, rather than high emission fractions.

By 2043, total baseline emissions decline across most compartments, reflecting projected reductions in the use of intentionally added microplastics under existing and anticipated regulatory and market trends, including impacts following UK alignment with EU regulation. This influence is largely driven by the close trading relationship between the United Kingdom and the EU, which encourages UK manufacturers to align product formulations with EU requirements to maintain market access and minimize production complexity. This decline does not reflect reduced demand or population changes alone, but rather the assumed phase-out and substitution of intentionally added microplastics in key product categories over time. The baseline scenario incorporates regulatory transition periods, reformulation of products, and partial alignment with EU REACH restrictions, which collectively lead to decreasing use volumes of microplastic-containing formulations despite broader market growth. As a result, emissions decrease even under continued product demand. Nevertheless, the overall intercompartmental

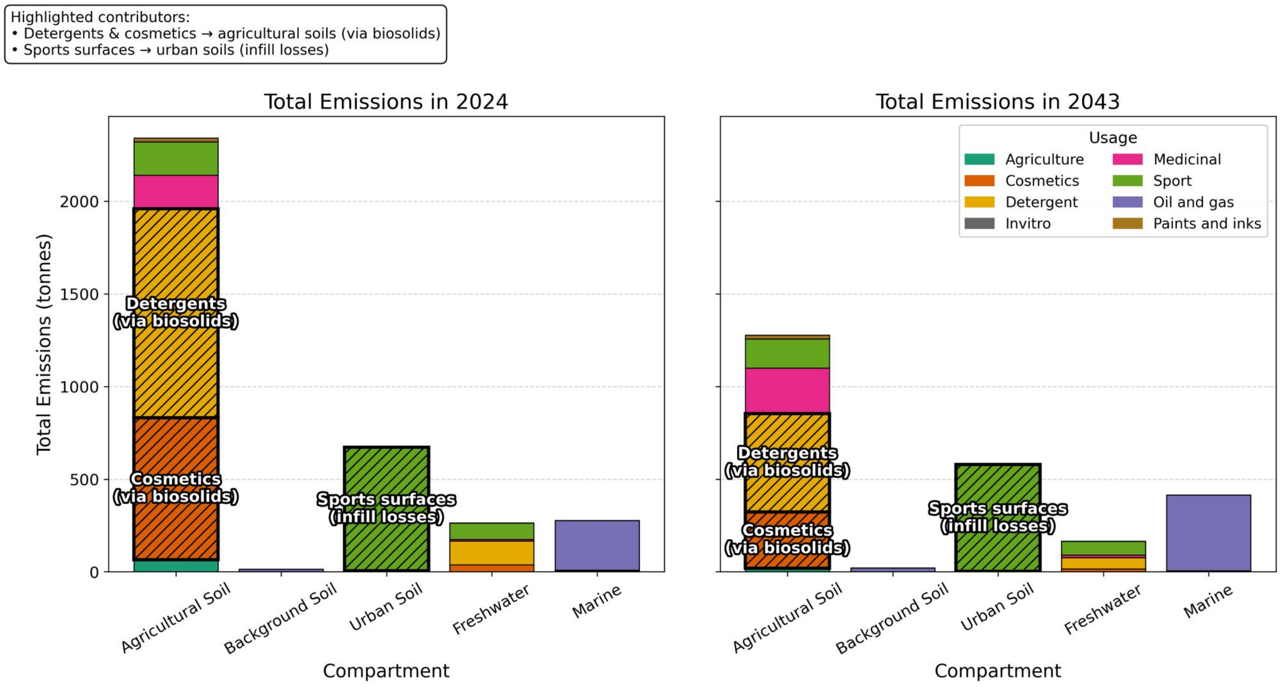

Figure 2 Baseline (business-as-usual) emissions of intentionally added microplastics by environmental compartment and broad-use sector in the United Kingdom for 2024 (left) and 2043 (right). Stacked bars show total annual emissions partitioned among agricultural soils, urban soils, background soils, freshwater, and the marine environment, with colors indicating contributing use sectors. Dominant contributing sectors are visually highlighted, illustrating the importance of detergents and cosmetics in agricultural soil contamination via sewage sludge application, and the predominance of materials used in synthetic sports surfaces in urban soils. Emissions to freshwater and marine compartments represent smaller fractions of total releases in both years.

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pattern of emissions remains consistent. Agricultural soils continue to be the dominant receiving environment, followed by urban soils, freshwater, and the marine compartment. While emissions from detergents and cosmetics decrease markedly by 2043, emissions from synthetic sports surfaces remain substantial because this sector is largely unaffected by the EU REACH restriction, reinforcing the contrast between these categories over the 2024–2043 period and maintaining sports surfaces as a key contributor to urban soil contamination.

Marine emissions are comparatively small in both years but increase slightly by 2043 due to cumulative transport from freshwater systems and persistent emissions from certain sectors, including oil and gas-related applications. Background soils (defined as soils not used for agricultural purposes or in urban areas) consistently receive negligible emissions relative to other compartments. It should be noted that this assessment primarily captures emissions from defined product-use pathways (i.e., point and semipoint sources associated with specific applications). Diffuse, nonpoint source emissions to terrestrial environments are accounted for in emissions from the application of biosolids. However, diffuse sources linked to recreational activities (e.g., outdoor use of cosmetics or detergents containing intentionally added microplastics) are not explicitly represented, although some aspects may be indirectly captured within broader emission categories such as urban runoff. We prioritized the dominant emission pathways, and so it is unlikely that the inclusion of such diffuse sources would lead to significantly different results.

The results for both scenario years highlight the central role of wastewater treatment and biosolid application in controlling the environmental distribution of intentionally added microplastics, as well as the influence of synthetic sports surfaces on urban soil contamination. The persistence of soil-dominated emissions across both time points underscores the importance of land-based pathways in shaping long-term exposure to intentionally added microplastics in the UK environment.

Exposure

Continuous exposure dynamics across environmental compartments

Long-term exposure to intentionally added microplastics was quantified as predicted environmental concentrations using the UTOPIA model, which simulates spatially averaged concentrations across 17 interconnected environmental compartments. Continuous baseline results for the period 1951–2043 are shown in Figure 3.

Across all compartments, PECs increase gradually following product introduction and accelerate in later decades as cumulative emissions increase, and environmental reservoirs build up. Freshwater and freshwater sediment compartments exhibit high relative exposure levels over time. This pattern is driven by direct inputs from synthetic sports surfaces via surface runoff and by down-the-drain emissions from detergents, cosmetics, and medicinal products, which enter aquatic systems following wastewater treatment.

Urban soils display a distinct exposure trajectory, dominated almost entirely by emissions from synthetic sports surfaces, with concentrations increasing rapidly with pitch area. Agricultural soils show substantial long-term accumulation, reflecting the dominant role of biosolid application as a pathway for microplastics retained during wastewater treatment. This dominance arises because many high-volume uses, such as cosmetics and detergents, release microplastics directly to wastewater, where treatment processes efficiently remove particles from the aqueous phase through settling and filtration, transferring them into sewage sludge rather than eliminating them. As a result, microplastics become concentrated in biosolids, which are predominantly applied to agricultural land (Defra, 2022; Harley-Nyang et al., 2022). Although concentration increases in agricultural soils occur more gradually than in aquatic sediments, these compartments act as persistent sinks, leading to elevated PECs by the end of the simulation period.

Marine waters exhibit the lowest predicted concentrations throughout the simulation period, despite direct emissions from sources related to oil and gas activities. This reflects the limited fraction of total emissions reaching this compartment and the high dilution capacity of the marine environment.

Overall, the results highlight that high emission volumes do not necessarily correspond to the highest environmental exposure. Transport processes, retention mechanisms, and compartment-specific dilution strongly influence resulting PECs. These dynamics underscore the importance of considering environmental fate and accumulation, rather than emissions alone, when assessing exposure to intentionally added microplastics.

Baseline exposure and uncertainty analysis

Baseline environmental concentrations of intentionally added microplastics were simulated for each broad use category using the dynamic UTOPIA model, with results reported for the first year of product use and for the final simulation year (2043). Predicted concentrations are presented across major environmental compartments, including freshwaters, sediments, soils, and air, with uncertainty ranges reflecting low- and high-baseline scenarios (see online supplementary material Figures S3-S10). In vitro diagnostic devices were excluded from the uncertainty assessment due to low use volumes.

Across all assessed categories, environmental concentrations increase substantially over time, reflecting cumulative emissions, environmental persistence, and gradual accumulation in receiving compartments. Urban soil consistently exhibits the highest predicted concentrations by 2043, followed by agricultural soil. Aquatic sediments represent an important secondary sink, while concentrations in freshwater and marine waters remain several orders of magnitude lower.

For products emitting primarily via wastewater pathways, such as detergents, cosmetics, and medicinal products, agricultural soils represent the main compartment in which exposure occurs. This pattern is driven by the high retention of microplastics in wastewater treatment sludge and its subsequent application to land. Concentrations in agricultural soils increase by many orders of magnitude between initial use and 2043, contrasting with the comparatively modest increases observed in exposure concentrations in freshwater, marine waters, and air.

Synthetic sports surfaces show a distinct exposure profile. Urban soils are the dominant receiving compartment throughout the simulation period, reflecting direct abrasion and loss of infill materials at the point of use. While early-year concentrations are

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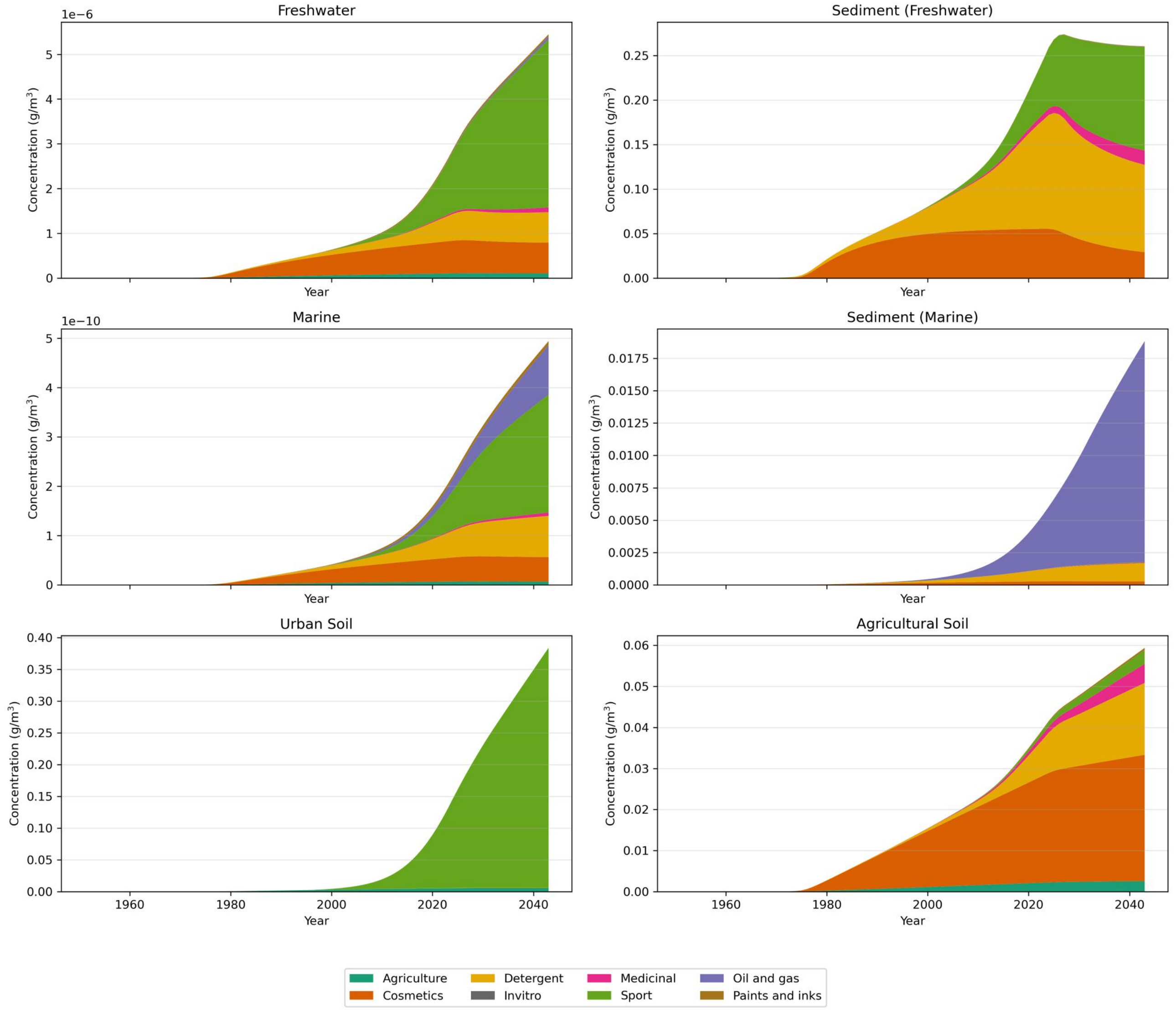

Figure 3 Continuous baseline predicted environmental concentrations (PECs) of intentionally added microplastics from 1951 to 2043 across major environmental compartments, simulated using the UTOPIA model. Stacked areas illustrate the contribution of broad-use sectors to spatially averaged concentrations in freshwater, freshwater sediments, marine water, marine sediments, urban soils, and agricultural soils. Results illustrate the temporal evolution of exposure, the accumulation of microplastics in soils and sediments, and the influence of transport and dilution processes on compartment-specific concentrations.

low due to limited installed surface area, concentrations increase sharply over time as surface coverage expands and cumulative losses accrue. Secondary transport pathways lead to measurable but much lower concentrations in freshwater and marine compartments.

Oil and gas applications and paints, inks, and coatings exhibit releases that led to exposure to a broader range of environmental compartments. These product sectors contribute to soil and sediment inputs through diffuse losses during use and weathering, with sediments becoming increasingly important sinks by 2043. Although absolute concentration remains lower than that associated with detergents or sports surfaces, their wide spatial distribution highlights their relevance for long-term environmental exposure.

Uncertainty analysis indicates that predicted concentrations span several orders of magnitude across low and high baseline scenarios, particularly in later years. Uncertainty is lowest in the early years of use, reflecting limited market penetration and lower cumulative emissions, and increases toward 2043 as uncertainty in historic use volumes and cumulative emissions propagate through the model. Soils and sediments exhibit the widest uncertainty ranges, consistent with their role as long-term accumulation compartments. Uncertainties in parameters controlling internal model processes, such as degradation and fragmentation, serve to amplify these uncertainties.

Overall, despite large uncertainties in absolute concentration values, the relative ranking of compartments and dominant exposure pathways is robust across all scenarios. Agricultural soil consistently represents the primary exposure compartment for wastewater-linked uses, while urban soils dominate for synthetic sports surfaces. These results underline the importance of land-based exposure pathways and cumulative accumulation in

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shaping long-term environmental exposure to intentionally added microplastics in the United Kingdom. Detailed descriptions of the uncertainty construction, including the derivation of low and high scenarios, smoothing, and scenario-consistency constraints, are provided in the online supplementary material.

Comparison of risk management options on environmental exposure

The effectiveness of six RMOs in reducing environmental exposure to intentionally added microplastics was evaluated relative to the baseline scenario, using percentage reductions in PECs across major environmental compartments (Figure 4).

Use-based restrictions (RMO 1A-1C) consistently deliver the highest exposure reduction potential across all compartments. Risk management option 1A, which proposes a broad restriction on nearly all uses of intentionally added microplastics, achieves the largest overall reductions, with exposure reductions exceeding 70%–90% in freshwater sediments and urban soils, and substantial reductions in freshwater and marine compartments. These results reflect the near-complete elimination of emissions across multiple pathways by 2043.

Risk management option 1B (RMO 1B) and risk management option 1C (RMO 1C) also achieve substantial exposure reductions, particularly in freshwater, freshwater sediments, and urban soils, though their effectiveness is lower than RMO 1A due to their narrower scopes, longer transition periods, and sector-specific derogations. Alignment with the EU REACH restriction under RMO 1C produces exposure reduction patterns similar to RMO 1B, indicating that targeted restrictions on high-emitting uses achieve a large proportion of the exposure reduction benefit.

Risk management option 2 (RMO 2), which introduces emission prevention measures for materials used in synthetic sports surfaces, shows strong compartment-specific effectiveness. Urban soil and freshwater sediments experience significant reductions in exposure, reflecting the dominant role of sports infill materials for emissions into these compartments. However, reductions in agricultural soil and marine environments are limited, as this option does not directly address wastewater-related pathways and subsequent releases to biosolids or via effluent.

The sewage sludge management options (RMO 3A and RMO 3B) primarily reduce exposure in agricultural soils, where biosolid application is the dominant pathway. Risk management option 3A (95% reduction in sludge recycling to land) achieves moderate reductions in agricultural soil exposure, while RMO 3B (50% reduction) yields smaller but measurable benefits. Soils are a less dynamic compartment, acting as a sink for microplastics. As a result, current and future exposures are strongly influenced by historic accumulation, and reductions in inputs only gradually translate into lower concentrations over time. Consequently, RMOs targeting these compartments show delayed effects within the simulation period to 2043. These options have minimal impact on urban soils and aquatic compartments, as they act only on a single downstream pathway rather than reducing emissions at source. In contrast, RMOs targeting upstream product use (RMO 1A–1C) reduce emissions across multiple pathways simultaneously, including wastewater, runoff, and direct environmental release, resulting in more comprehensive reductions in environmental exposure. Downstream measures (RMO 2 and RMO 3), while effective, are limited to specific sources or pathways and therefore produce more localized and compartment-specific
benefits.

Overall, the comparison demonstrates that RMOs targeting upstream product use (RMO 1A–1C) provide the most comprehensive reductions in environmental exposure, while downstream measures (RMO 2 and RMO 3) are effective in addressing

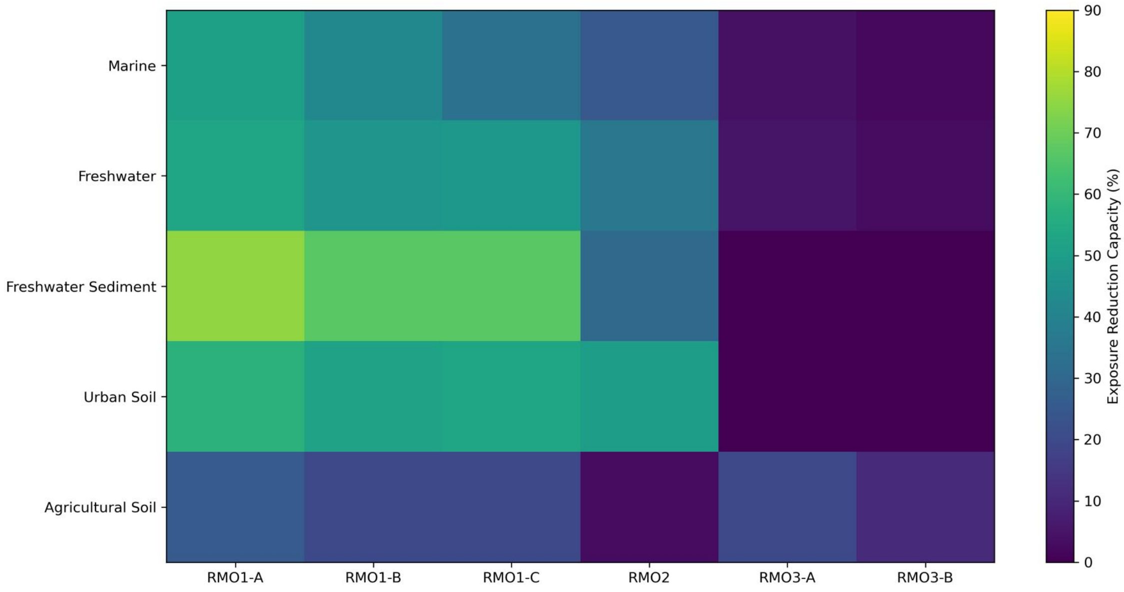

Figure 4 Percentage reduction in predicted environmental concentrations (PECs) of intentionally added microplastics in 2043 relative to the baseline scenario for six risk management options (RMOs). Results are shown for major environmental compartments, illustrating the relative effectiveness of broad use restrictions (RMO 1A–1C), emission prevention measures for synthetic sports surfaces (RMO 2), and reductions in sewage sludge recycling to land (RMO 3A–B).

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specific compartments and pathways. These findings emphasize the importance of combining broad regulatory controls with targeted emission management to maximize exposure reduction across the environment.

Discussion

This assessment demonstrates that emissions of intentionally added microplastics in the United Kingdom are dominated by land-based pathways, with soils, particularly urban soils, acting as the primary long-term receiving environments. This finding aligns with an increasing body of evidence indicating that terrestrial systems may represent the largest environmental reservoirs of microplastics, despite historically receiving less research attention than aquatic environments. Urban soils are dominated by direct emissions from synthetic sports surfaces, highlighting the importance of use-location and product design in shaping exposure patterns. This underscores the importance of studies assessing the hazards and risks of microplastics in terrestrial environments, which have seen less attention and are therefore much more data-poor than aquatic environments. While the data are more limited, some recent studies are beginning to bring together soil ecotoxicity data to support such assessments (Redondo-Hasselerharm et al., 2024; Tunali et al., 2023).

The results show that high emission volumes do not necessarily translate into high environmental exposure, serving as a warning to regulatory assessments that rely solely on emissions as a proxy for risk. For example, oil and gas applications contribute directly to marine environments, yet predicted concentrations remain low due to the high dilution capacity of marine waters. Conversely, products with lower use volumes but efficient emission pathways, such as detergents and cosmetics, produce disproportionately high exposure in soils via wastewater-derived biosolids. These patterns demonstrate that environmental fate, transport, and retention processes strongly determine exposure outcomes. Different actions may be needed to reduce emissions to specific environments. Relative assessments of risk to key ecosystems will be necessary to prioritize where actions to reduce exposure are most needed. From a regulatory perspective, this implies that effective mitigation strategies must be pathway-specific: Measures aimed at protecting freshwater and marine ecosystems must primarily target wastewater emissions, whereas reducing soil exposure requires interventions focused on sludge management, land application practices, and direct-use emissions to land.

Emissions associated with oil and gas-related applications were projected, assuming continuation of current activity trends, and did not explicitly incorporate potential future changes linked to UK decarbonization policies. In practice, reductions in fossil fuel production and use under energy transition pathways could lead to declining emissions from this sector. However, the magnitude of any reduction remains uncertain, as domestic demand decreases may be partially offset by continued production for export or by the long operational lifetimes of existing infrastructure. Future trajectories of these emissions will therefore depend strongly on broader energy transition dynamics.

The continuous baseline exposure analysis highlights the cumulative nature of microplastic pollution. Predicted environmental concentrations increase steadily following product introduction and accelerate in later decades, reflecting both increasing use and limited degradation. Soils and sediments act as long-term accumulation compartments, consistent with previous modeling and empirical studies showing that these environments function as long-term sinks for particulate contaminants. The persistence of these compartments implies that even substantial future emission reductions may take decades to translate into meaningful reductions in environmental exposure. This legacy effect is especially pronounced for soils, where accumulated microplastics may remain for extended periods, reinforcing concerns regarding chronic exposure and potential long-term ecological impacts. These are typically understudied as compared to more standard acute toxicity testing, but seem particularly relevant when considering the long-term impacts of microplastic accumulation in these environments.

While absolute exposure levels are subject to considerable uncertainty, spanning several orders of magnitude in later years, the relative ranking of compartments and dominant pathways remains robust across low and high scenarios. Uncertainty increases over time due to compounding assumptions in historic use, emission factors, and cumulative accumulation. Nevertheless, all scenarios consistently identify soils and sediments as the primary exposure compartments. Continued empirical research, particularly on historic use volumes, emission fractions, and environmental retention processes, would help reduce uncertainty in future assessments. The structured uncertainty framework applied in this study ensures continuity between historic reconstructions and future projections while avoiding implausible artifacts.

Comparison of RMOs reveals clear differences in their ability to reduce environmental exposure. Broad upstream restrictions on the use of intentionally added microplastics (RMO 1A–1C) achieve the most comprehensive exposure reductions across all compartments because they act at the source, preventing emissions before they enter any environmental pathway. By reducing or eliminating microplastics in products, these measures simultaneously limit releases to wastewater, urban runoff, and direct emissions to soils and surface waters. This multipathway reduction leads to consistent decreases across all receiving compartments, including soils, freshwater, and marine environments. Risk management option 1A (RMO 1A), in particular, delivers high reduction efficiency in several compartments by 2043, reflecting its wide scope and limited exemptions. However, the value of the modeling framework lies not only in confirming the effectiveness of broad restrictions but in quantifying how different policy designs influence specific pathways, time dynamics, and environmental compartments. For example, the results highlight that downstream measures can achieve rapid reductions in targeted compartments but are constrained by legacy accumulation and pathway specificity. This distinction would not be apparent from emission-based assessments alone.

Targeted measures demonstrate pathway-specific effectiveness. Risk management option 2 (RMO 2) substantially reduces exposure in urban soils and freshwater by addressing emissions from synthetic sports surfaces, while sewage sludge management options (RMO 3A and 3B) primarily reduce exposure in agricultural soils. These findings support the growing consensus that combining upstream source control with targeted downstream interventions provides the most effective strategy for

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managing diffuse pollutants. These downstream measures are less effective in isolation but offer cost-effective, complementary benefits and additional co-benefits through reduced exposure to other contaminants in biosolids, which RMOs 1 and 2 cannot achieve. These results further indicate that greater overall reductions in environmental exposure can be achieved through the combined implementation of complementary RMOs by simultaneously targeting multiple emission pathways and environmental compartments. Together, the results suggest that no single RMO is sufficient to address all exposure pathways. Instead, an integrated approach combining upstream use restrictions with targeted downstream measures is likely to provide the greatest overall emission and exposure reduction benefit.

A key contribution of this study is the integration of emissions, environmental fate, and exposure within a single framework, enabling comparison of policy options beyond simple emission reduction metrics. This allows identification of mismatches between emission reductions and exposure outcomes, reflecting the influence of environmental persistence and accumulation on long-term exposure patterns. Such insights are particularly relevant for microplastics, where reductions in emissions may not translate proportionally into changes in environmental concentrations over the modeled timeframe. The framework, therefore, provides a tool for evaluating not only the magnitude of policy impacts but also their distribution across environmental compartments, which are critical considerations for effective policy design. A key limitation is the substantial uncertainty associated with the fate and transformation processes that govern microplastic retention and redistribution, particularly degradation and fragmentation. Environmental degradation rates remain poorly constrained and are likely to vary by polymer type, particle size and shape, additive content, and receiving environment (e.g., soils, surface waters, sediments), as well as by site-specific conditions such as temperature, UV exposure, oxygen availability, and microbial activity. Fragmentation is similarly uncertain: The rate at which particles fragment, and the resulting fragment size distribution, can differ markedly across environments and mechanisms (e.g., mechanical abrasion, photodegradation, and biotic interactions), and empirical data linking these processes to field-relevant timescales are limited. Because these processes directly affect particle size distributions, settling and resuspension behavior, aggregation/biofouling dynamics, and ultimately exposure metrics expressed as either mass or particle number, their uncertainty propagates through the model and can amplify over time, especially in long-term accumulation compartments such as soils and sediments. More generally, exposure modeling for microplastics is sensitive to the combined uncertainty in historic use reconstruction, emission fractions, wastewater and sludge routing, and environmental transport parameters, meaning that absolute concentration estimates should be interpreted cautiously. In addition, uncertainties in input data and model structure mean that results should be interpreted as scenario-based estimates rather than precise predictions, particularly for long-term projections. Continued empirical research to constrain degradation and fragmentation rates under realistic environmental conditions, alongside improved monitoring data for terrestrial compartments, would substantially strengthen future exposure assessments.

Finally, it is worth reflecting that this assessment only covers intentionally added microplastics, which are a small but notable part of the total emissions of microplastics to the environment. Secondary sources of microplastic releases, such as tire wear and textile abrasion, likely dominate real-world emissions. For example, at the European Union level, emissions from tire wear are approximately sixfold larger than emissions from intentionally added microplastics (Quik et al., 2024). However, although not the most important release forms by mass, intentionally added microplastic emissions are not negligible and represent greater emissions than from sectors such as packaging and agriculture. Importantly, from a policy context, source control and mitigation measures are much easier to implement for intentionally added than for secondary microplastics, and so action on intentionally added microplastics could be seen as an “easy win.” Addressing this emission category, therefore, represents a practical early step in broader efforts to reduce total microplastic pollution, although comprehensive assessments integrating both primary and secondary sources will be essential for long-term prioritization of policy interventions.

Overall, this study provides a comprehensive assessment of the emissions, environmental fate, and exposure of intentionally added microplastics in the United Kingdom from their introduction to 2043. The results demonstrate that land-based environments, particularly sediments and urban soils, are the dominant sinks for intentionally added microplastics, driven by wastewater treatment practices and direct emissions from synthetic sports surfaces. Predicted environmental concentrations increase over time due to cumulative emissions and persistence, with soils and sediments acting as long-term reservoirs. While substantial uncertainty remains in absolute exposure levels, the dominance of land-based pathways and accumulation compartments is consistent across all scenarios.

Evaluation of RMOs shows that broad restrictions on the use of intentionally added microplastics offer the most effective and comprehensive reductions in environmental exposure. Targeted and downstream measures provide important complementary benefits, particularly when addressing specific pathways such as sports surface infill losses and sewage sludge application. These findings support regulatory strategies that prioritize upstream prevention while recognizing the value of complementary, pathway-specific controls.

The framework developed here highlights the importance of integrating emissions, fate, exposure, and policy analysis when assessing microplastic pollution. It provides a robust basis for informing regulatory decisions and can be readily adapted to assess future scenarios or applied in other regional contexts.

Supplementary material

Supplementary material is available at *Integrated Environmental Assessment and Management* online.

Data availability

The calculations and methodological details supporting this study are described in the online supplementary material. The modeling

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framework used for the analysis is openly available on GitHub at: [https://github.com/microplastics-cluster/UTOPIA_model].

The baseline central exposure results for each broad product category, together with the corresponding emission data (tons/year) for the period 2024-2043, are available through Zenodo at: [10.5281/zenodo.18944430].

Author contributions

Cansu Uluseker (Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing—original draft, Writing—review & editing), Hongyan Chen (Data curation, Formal analysis, Methodology, Writing—review & editing), Thea Sletten (Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Writing—review & editing), Oliver Pilkington (Conceptualization, Data curation, Formal analysis, Methodology, Writing—review & editing), Sarah Roberts (Formal analysis, Methodology, Writing—review & editing), David Spurgeon (Funding acquisition, Investigation, Methodology, Supervision, Writing—review & editing), Richard K. Cross (Funding acquisition, Investigation, Supervision, Writing—review & editing), and Sam Harrison (Formal analysis, Funding acquisition, Methodology, Supervision, Writing—review & editing)

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Conflicts of interest

The authors declare that they have no competing interests.

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